NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4219

PROPELLANT VAPORIZATION AS A CRITERION FOR ROCKET ENGINE DESIGN; RELATION BETWEEN PERCENTAGE OF PROPELLANT VAPORIZED AND ENGINE PERFORMANCE

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SUMMARY

An analysis is presented on the quantitative effect of incomplete propellant vaporization on rocket-engine performance. A relation between characteristic exhaust velocity c* and the percentages of oxidant and fuel vaporized and burned is given. The analysis shows that c* efficiencies of 70 to 90 percent can be realized when only half the fuel is vaporized, whereas c* efficiencies of about 60 percent can be realized when half the oxidant is vaporized. The specific relations between c* and propellant vaporized are presented graphically for the hydrogen-fluorine, hydrogen-oxygen, ammonia-fluorine, and JP-4 - oxygen propellant combinations. The analysis is applied to experimental data for these propellant combinations.

INTRODUCTION

Characteristic exhaust velocity is commonly used as an experimental measure of the completeness of combustion in rocket engines. This parameter may indicate inefficiencies in the combustion process that may be due to incomplete reaction, mixing, propellant vaporization, and other causes. Reported herein is an analysis relating the characteristic exhaust velocity to the percentage of propellant vaporized.

Propellant vaporization is considered in this report as the factor that limits the rate at which the combustion process proceeds within a rocket engine. The importance of propellant vaporization is also emphazised in references 1 to 3. The analytical studies of references 4 and 5 are based on the hypothesis that the combustion rate is completely governed by the rate of propellant vaporization. Qualitatively, these analyses are in agreement with experimental results. Exact comparisons of experimental and analytical results, however, require further refinements in the interpretation of data. For this purpose, a method of data

analysis has been devised to relate experimental c^* data to the percentage of propellant vaporized.

The treatment of experimental data reported herein is consistent with the analytical combustion model used in droplet-vaporization calculations reported in references 4 and 5. Application of the method of analysis to the hydrogen-fluorine, hydrogen-oxygen, ammonia-fluorine, and JP-4 - oxygen propellant combinations is described.

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SYMBOLS

A_t	nozzle throat diameter, sq in.
c^*	characteristic exhaust velocity, ft/sec
$\mathcal{F}$	fuel vaporized, percent
g	gravitational constant, 32.2 ft/sec^2
$\mathcal{O}$	oxidant vaporized, percent
P_c	total chamber pressure, lb/sq in. abs
w_f	fuel weight flow, lb/sec
w_o	oxidant weight flow, lb/sec
η_c^*	characteristic-velocity efficiency, percent of theoretical

Subscripts:

exp	experimental
$\mathcal{O}/\mathcal{F}$	ratio of vaporized oxidant to vaporized fuel weight flow, $\mathcal{O}w_o/\mathcal{F}w_f$
$\mathcal{O}/f$	ratio of vaporized oxidant to fuel weight flow, $\mathcal{O}w_o/w_f$
$o/\mathcal{F}$	ratio of oxidant to vaporized fuel weight flow, $w_o/\mathcal{F}w_f$
o/f	oxidant-fuel weight ratio, w_o/w_f
th	theoretical

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THEORY

A mixture of oxidant and fuel drops vaporizing in an atmosphere of their combustion products is assumed for the combustion model in this analysis. For incomplete combustion, the rocket exhaust comprises a mixture of oxidant drops, fuel drops, and gaseous combustion products. The gaseous combustion products are assumed to be at thermodynamic equilibrium concentrations. If the volume and kinetic energy of the liquid drops are neglected, the characteristic velocity c^* that can be theoretically realized may be computed from the thermodynamic properties of the combustion products and related to combustion-chamber parameters by the following equation from reference 6:

$$(c_{th}^*)_{\mathcal{O}/\mathcal{F}} = \frac{P_c A_t g}{\mathcal{O} w_o + \mathcal{F} w_f} \tag{1}$$

The experimental c^* in terms of measured engine parameters is expressed

$$(c_{exp}^*)_{o/f} = \frac{P_c A_t g}{w_o + w_f} \tag{2}$$

Combining equations (1) and (2) gives

$$(c_{exp}^*)_{o/f} = (c_{th}^*)_{\mathcal{O}/\mathcal{F}} \frac{\mathcal{O} w_o + \mathcal{F} w_f}{w_o + w_f} \tag{3}$$

The c^* efficiency η_{c^*} is usually taken to be

$$(\eta_{c^*})_{o/f} = \frac{(c_{exp}^*)_{o/f}}{(c_{th}^*)_{o/f}} \tag{4}$$

Combining equations (3) and (4) gives

$$(\eta_{c^*})_{o/f} = \frac{(c_{th}^*)_{\mathcal{O}/\mathcal{F}}}{(c_{th}^*)_{o/f}} \left(\frac{\mathcal{O} w_o + \mathcal{F} w_f}{w_o + w_f}\right) \tag{5}$$

Equation (5) relates c^* efficiencies to the percentages of fuel and oxidant vaporized and may be used for the interpretation of experimental data.

The percentages of fuel and oxidant vaporized are parameters that cannot be readily evaluated for most rocket engine tests. A simplifying assumption that may satisfy many operational conditions, however, is to consider either the oxidant or the fuel completely vaporized at the

exhaust nozzle. Such a combustion model was assumed for droplet-vaporization computations reported in references 4 and 5. With this assumption equation (5) may be used to convert a measured c^* efficiency into the percentage of the propellant vaporized. The expressions for these conditions follow.

With the fuel completely vaporized, the c^* efficiency is related to the fraction of oxidant vaporized by

$$(\eta_{c^*})_{o/f} = \frac{(c^*_{th})_{\mathcal{O}/f}}{(c^*_{th})_{o/f}}\left(\frac{\dfrac{\mathcal{O} w_o}{w_f} + 1}{\dfrac{w_o}{w_f} + 1}\right) \tag{6}$$

With the oxidant completely vaporized, the c^* efficiency is related to the fraction of fuel vaporized by

$$(\eta_{c^*})_{o/f} = \frac{(c^*_{th})_{o/\mathcal{F}}}{(c^*_{th})_{o/f}}\left(\frac{\dfrac{w_o}{w_f} + \mathcal{F}}{\dfrac{w_o}{w_f} + 1}\right) \tag{7}$$

Such computations require a knowledge of the variation in theoretical c^* over an extended range of mixture ratios. These variations for several propellant combinations are shown in figure 1. Theoretical values reported in references 7 to 9 were extrapolated over the region shown. The extrapolations were based on the assumptions that: (1) for low percentages of oxidant and fuel, the combustion temperature varies directly as the percentage of fuel or oxidant in the mixture and (2) c^* is proportional to the square root of the combustion temperature.

The theoretical c^* values shown in figure 1 were used to obtain graphical representations of the relation between c^* and percentage of propellant vaporized. These graphical representations include the variation of c^* efficiency with the percentage of oxidant vaporized and the percentage of fuel vaporized, as expressed by equations (6) and (7), respectively. Application of these curves to estimating the percentage of vaporized propellant from experimental data is discussed in the following section.

RESULTS AND DISCUSSION

Effect of Incomplete Vaporization on Engine Performance

The variations of c^* with percentages of fuel and oxidant vaporized are shown in figures 2 to 5 for the hydrogen-fluorine, hydrogen-oxygen, ammonia-fluorine, and JP-4 - oxygen propellant combinations. For all

propellant combinations, a higher c^* is obtained with a given percentage of fuel vaporized than with an equal percentage of oxidant; for example, with half the fuel vaporized, the c^* efficiency is between 70 and 90 percent, whereas with half the oxidant vaporized, the c^* efficiency is about 60 percent. This difference is attributable to several factors, including the shape of the theoretical c^* curve, the fact that peak theoretical c^* occurs in the fuel-rich region, and the fact that the oxidant weight flow accounts for a large part of the total propellant flow.

Figures 2 to 5 may be used to interpret experimental c^* performance in terms of the percentage of fuel or oxidant vaporized provided the other propellant can be assumed to be completely vaporized. For example, for the ammonia-fluorine propellant combination, a c^* efficiency of 85 percent at an oxidant-fuel ratio of 3.0 may indicate that only 60 percent of the ammonia (and all the fluorine) or 80 percent of the fluorine (and all the ammonia) has vaporized. The following table presents a similar comparison for other propellant combinations:

Propellant	c^* Efficiency, percent	w_o/w_f	Fuel vaporized, $\mathscr{F}$, percent	Oxidant vaporized, $\mathscr{O}$, percent
Hydrogen-fluorine	85	4.0	37	82
Hydrogen-oxygen	85	2.0	51	80
Ammonia-fluorine	85	3.0	60	80
JP-4 - oxygen	85	2.5	70	79

The results may be further interpreted to show the percentages of propellants that must actually be burned to obtain a given c^* efficiency level. For example, with hydrogen and fluorine, only 37 percent of the hydrogen need evaporate and completely consume the fluorine in order to obtain a c^* efficiency of 85 percent at an oxidant-fuel weight ratio of 4.0. This, in effect, is the c^* efficiency obtained if the 37 percent is completely vaporized and the fluorine completely burned in the chamber and the remaining 63 percent is lost as liquid.

Interpretation of Experimental Data

Typical experimental variation of c^* efficiency with chamber length (data from ref. 10) is shown in figure 6 for a single-element injector with JP-4 and oxygen. The c^* efficiency data are also evaluated in terms of the percent oxidant vaporized and the percent fuel vaporized, assuming in each case that the other propellant is completely vaporized.

An explicit evaluation of the percentage of propellant vaporized cannot be made if incomplete vaporization of both oxidant and fuel is assumed; probably neither the oxygen nor the hydrocarbon vaporized completely in the experiments reported in reference 10. Each value of c^* efficiency, however, may be expressed as a specific relation between the percentages of oxidant and fuel vaporized. These relations are shown in figure 7 for oxygen with JP-4 and may be applied to the experimental data shown in figure 6.

These methods of data analysis provide a means of correlating droplet-evaporation calculations (e.g., refs. 4 and 5) with experimental engine performance.

The shape of the c^* efficiency curve in figure 6 is typical for most injectors and propellant combinations. It will be used as a hypothetical curve for several propellant combinations to illustrate the importance of propellant vaporization. The variations in the percentages of fuel and oxidant vaporized for various propellants are shown in figure 8 at the oxidant-fuel ratio for peak theoretical performance. With oxidant vaporization controlling the reaction, the c^* efficiency is slightly greater than the percentage of oxidant vaporized, regardless of the propellant combination. With fuel vaporization controlling, however, the results show that c^* efficiency is significantly higher than the percentage of fuel vaporized and that this difference is greater for hydrogen than for JP-4 or ammonia. The validity of these evaluations depends on whether complete vaporization of one propellant can justifiably be assumed. Injector design features and propellant physical properties are factors that influence this assumption.

SUMMARY OF RESULTS

An analysis is presented on the quantitative effect of incomplete propellant vaporization on engine performance. An expression relating characteristic exhaust velocity to the percentages of fuel and oxidant vaporized and burned is given. A graphical representation of the relation is presented for the hydrogen-fluorine, hydrogen-oxygen, ammonia-oxygen, and JP-4 - oxygen propellant combinations. If the vaporization of one propellant is assumed to control the extent of reaction, this evaluation shows that, at mixture ratios for peak theoretical performance, c^* efficiencies of about 60 percent are obtained with half the oxidant vaporized, and c^* efficiencies from 70 to 90 percent are obtained with half the fuel vaporized. Efficiencies are highest for the hydrogen fuels.

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National Advisory Committee for Aeronautics
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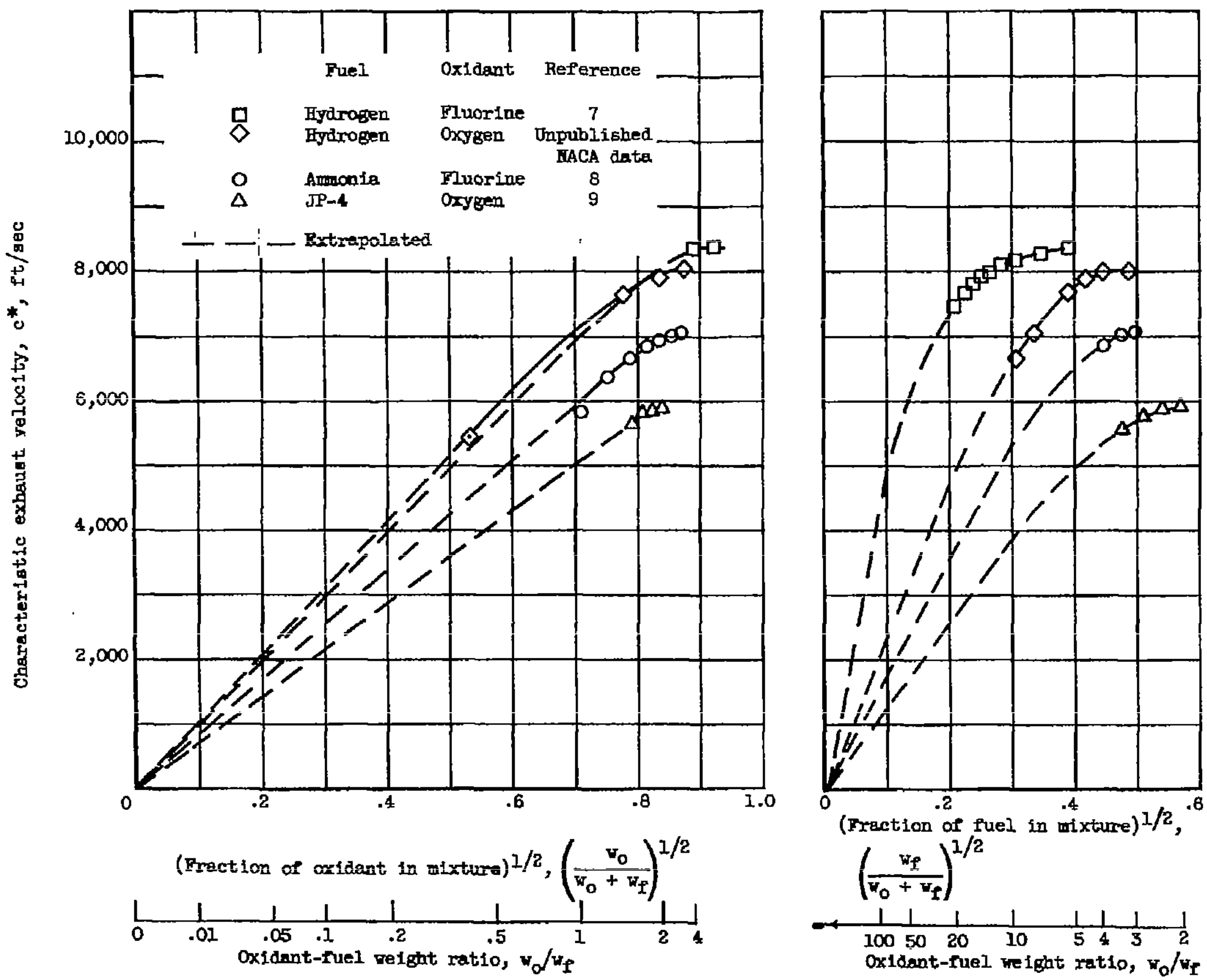
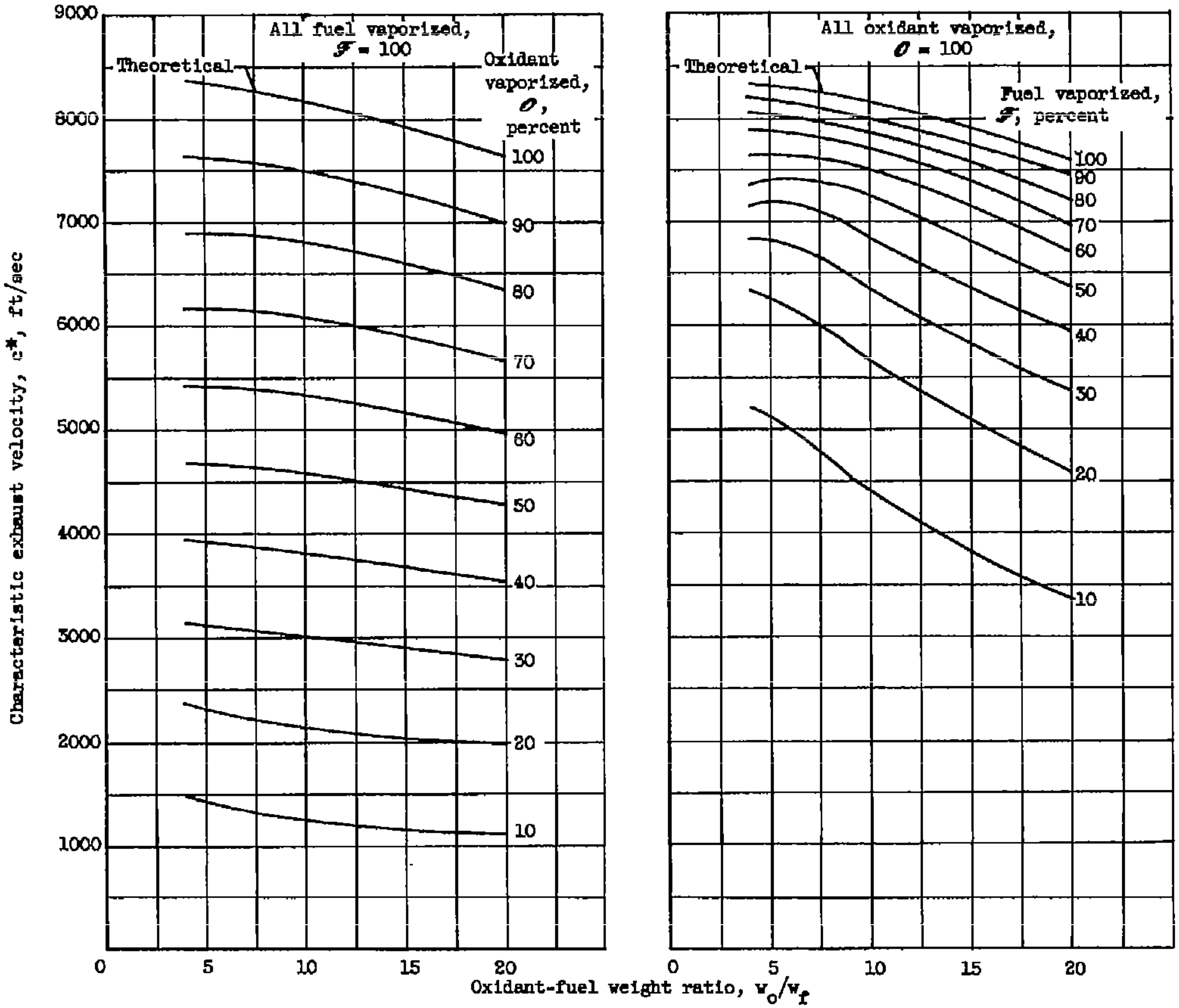
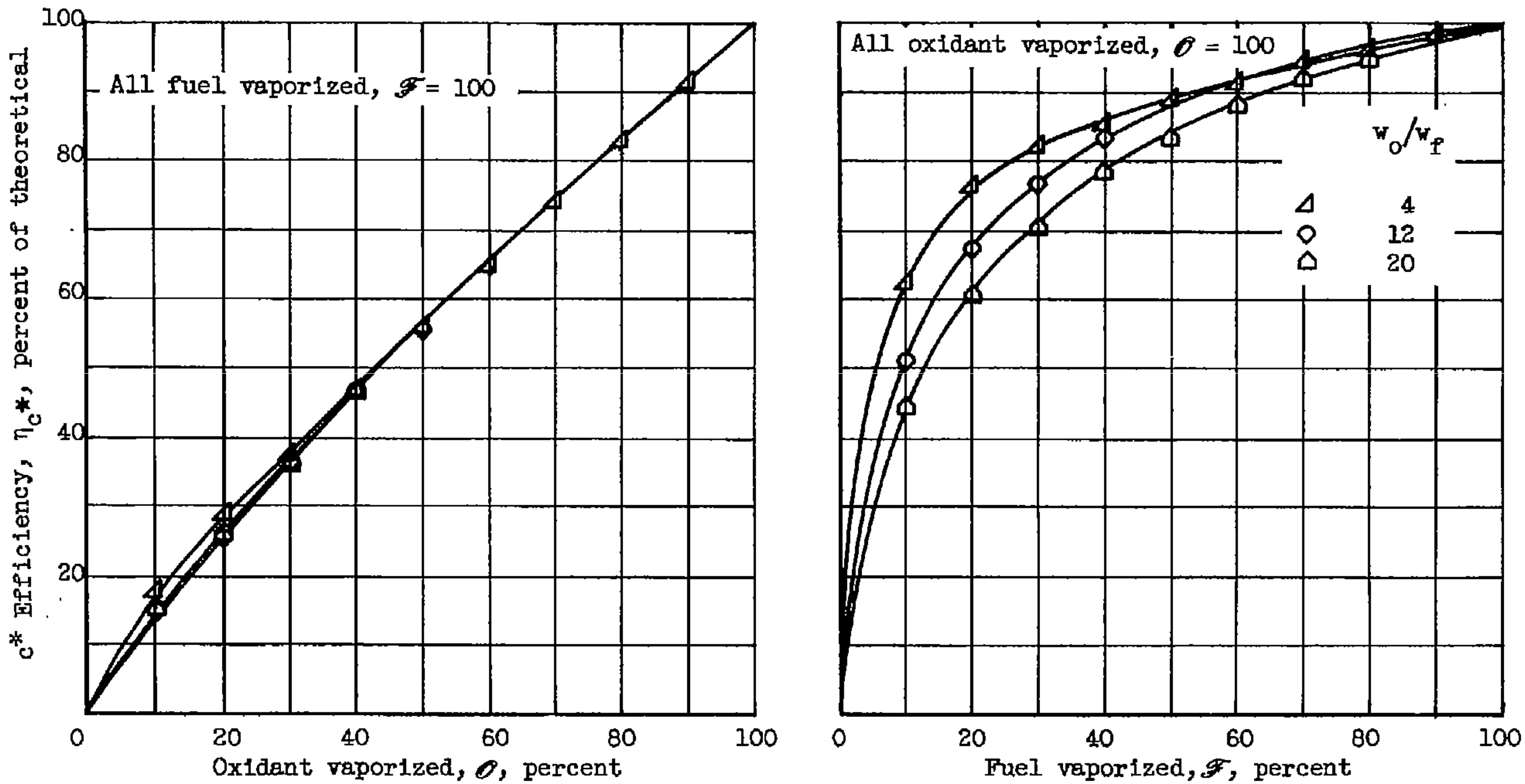


Figure 1. - Variation of theoretical characteristic exhaust velocity with mixture ratio for several propellant combinations at combustion-chamber pressure of 300 pounds per square inch absolute and equilibrium expansion.



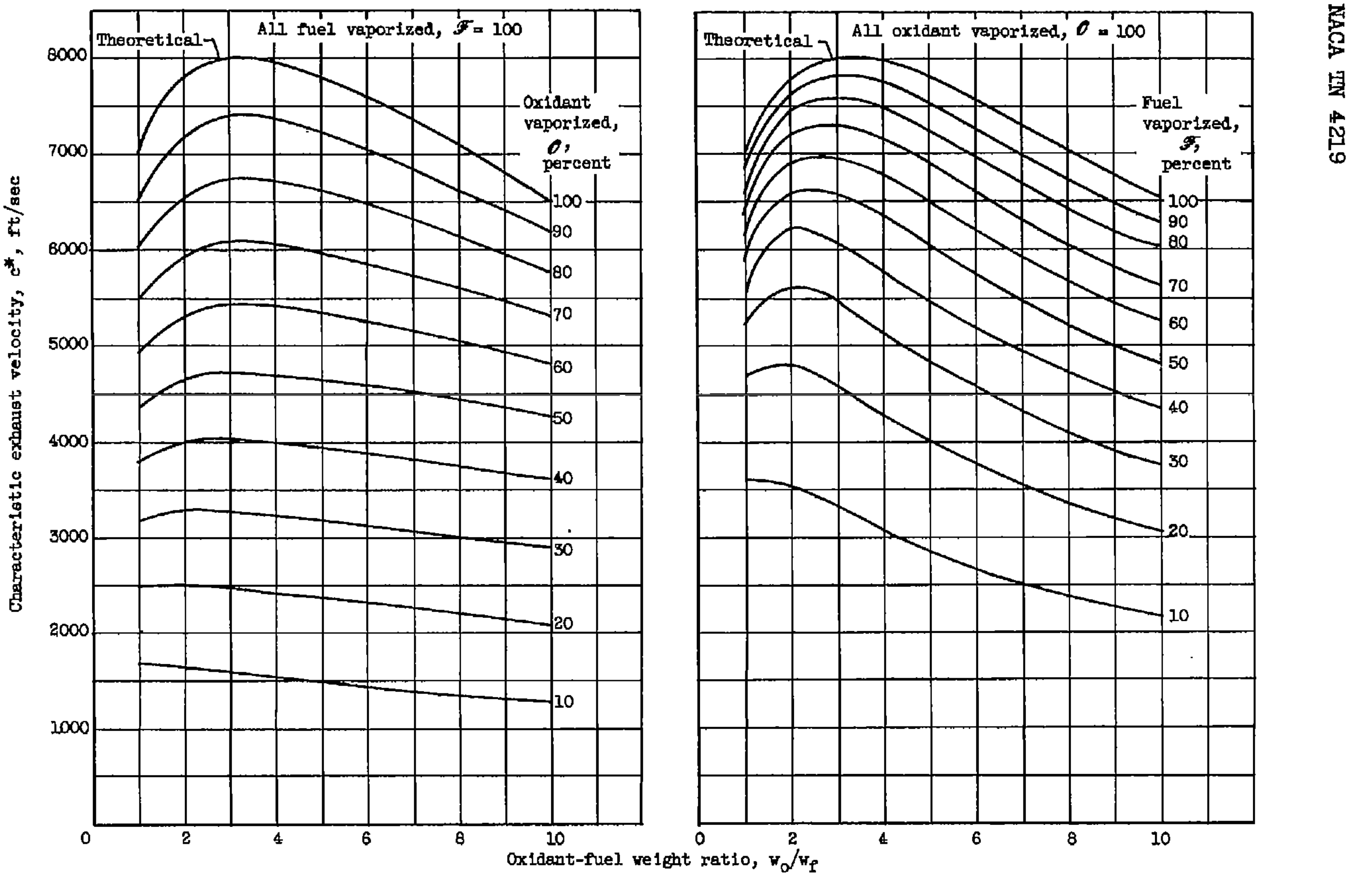
(a) Variation of c* with mixture ratio.

Figure 2. - Effect of incomplete vaporization on c* and c* efficiency for hydrogen and fluorine.



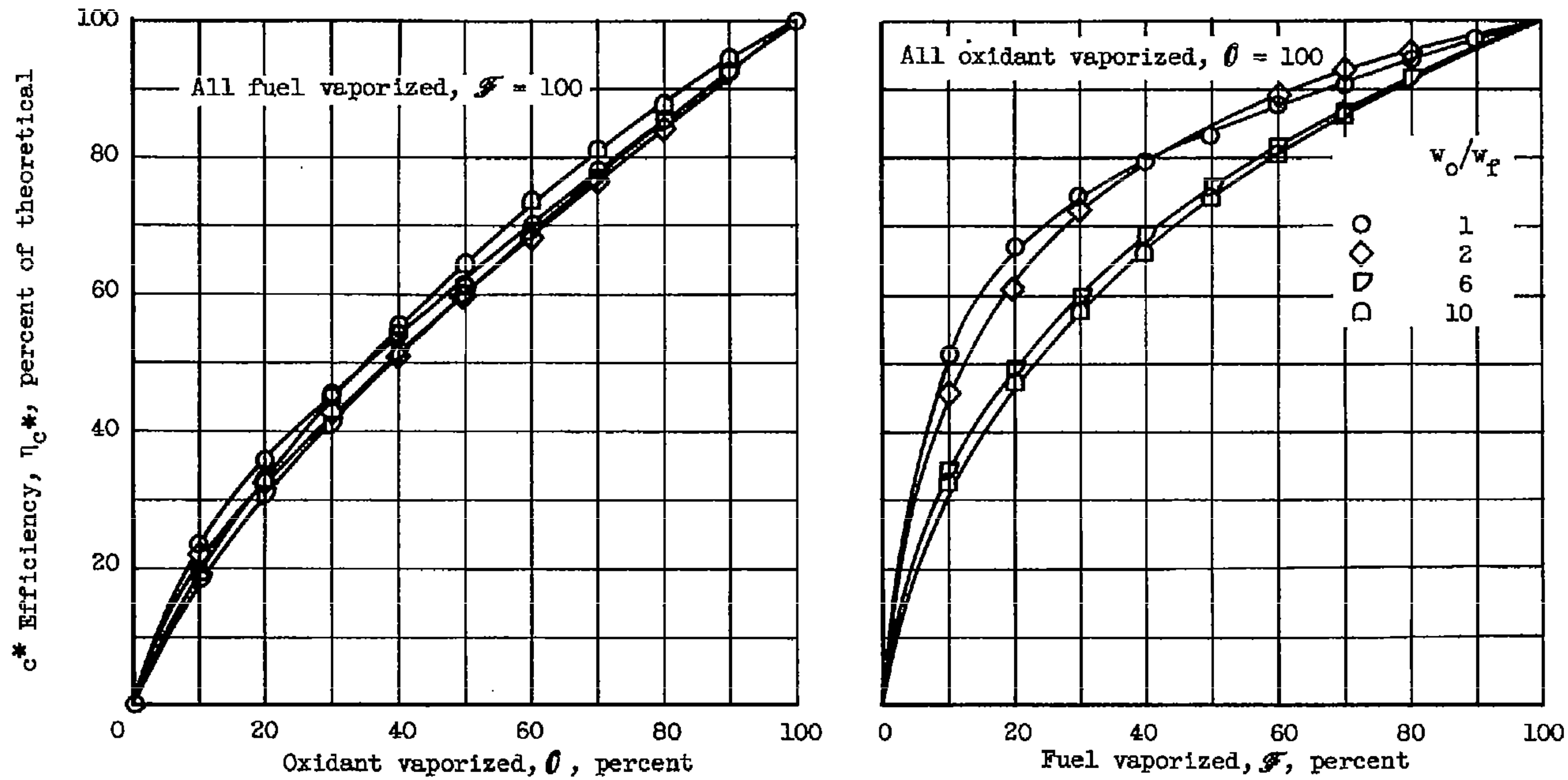
(b) Variation of c* efficiency with percentage of propellant vaporized.

Figure 2. - Concluded. Effect of incomplete vaporization on c* and c* efficiency for hydrogen and fluorine.



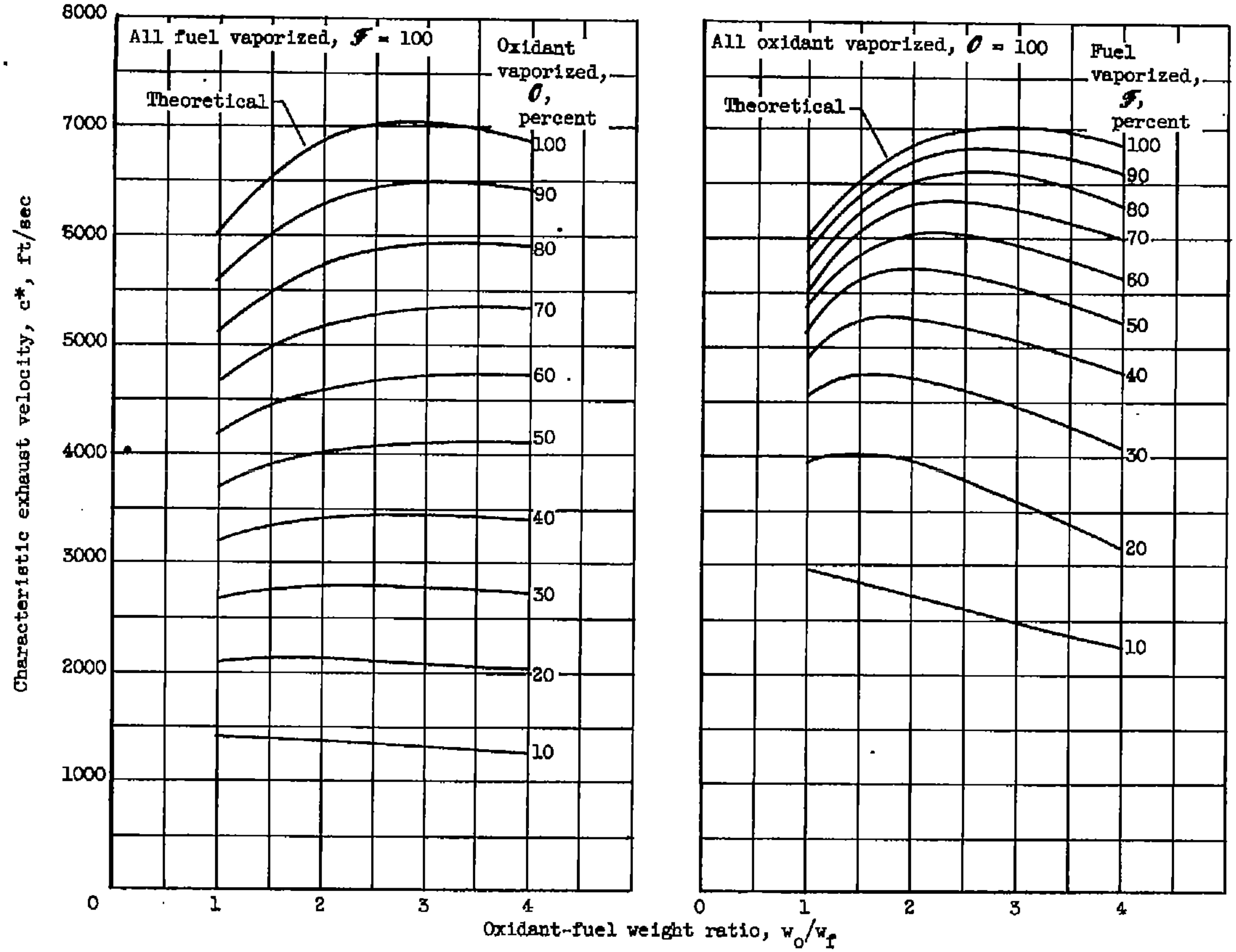
(a) Variation of c^* with mixture ratio.

Figure 3. - Effect of incomplete vaporization on c^* and c^* efficiency for hydrogen and oxygen.



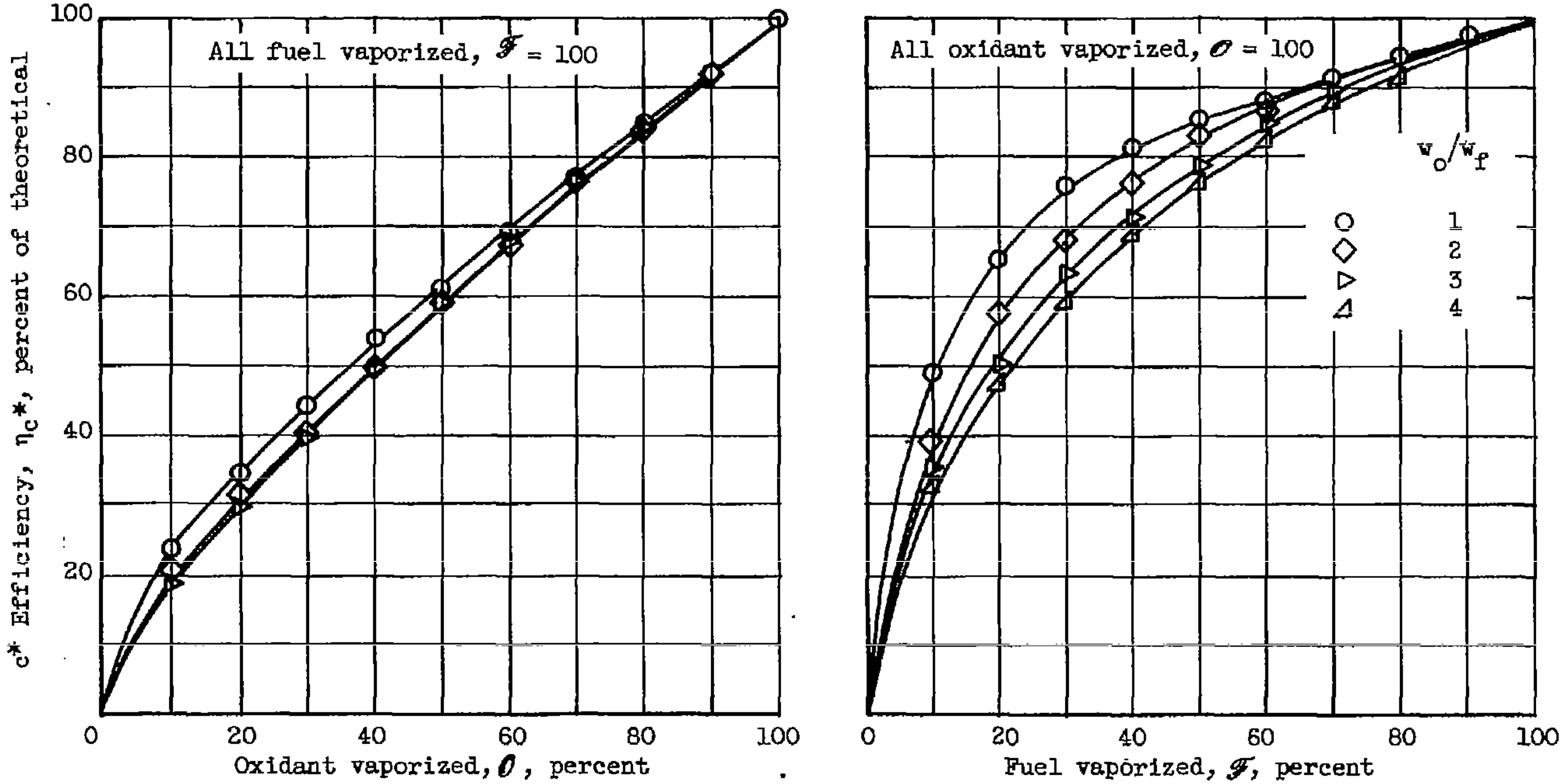
(b) Variation of c* efficiency with percentage of propellant vaporized.

Figure 3. - Concluded. Effect of incomplete vaporization on c* and c* efficiency for hydrogen and oxygen.



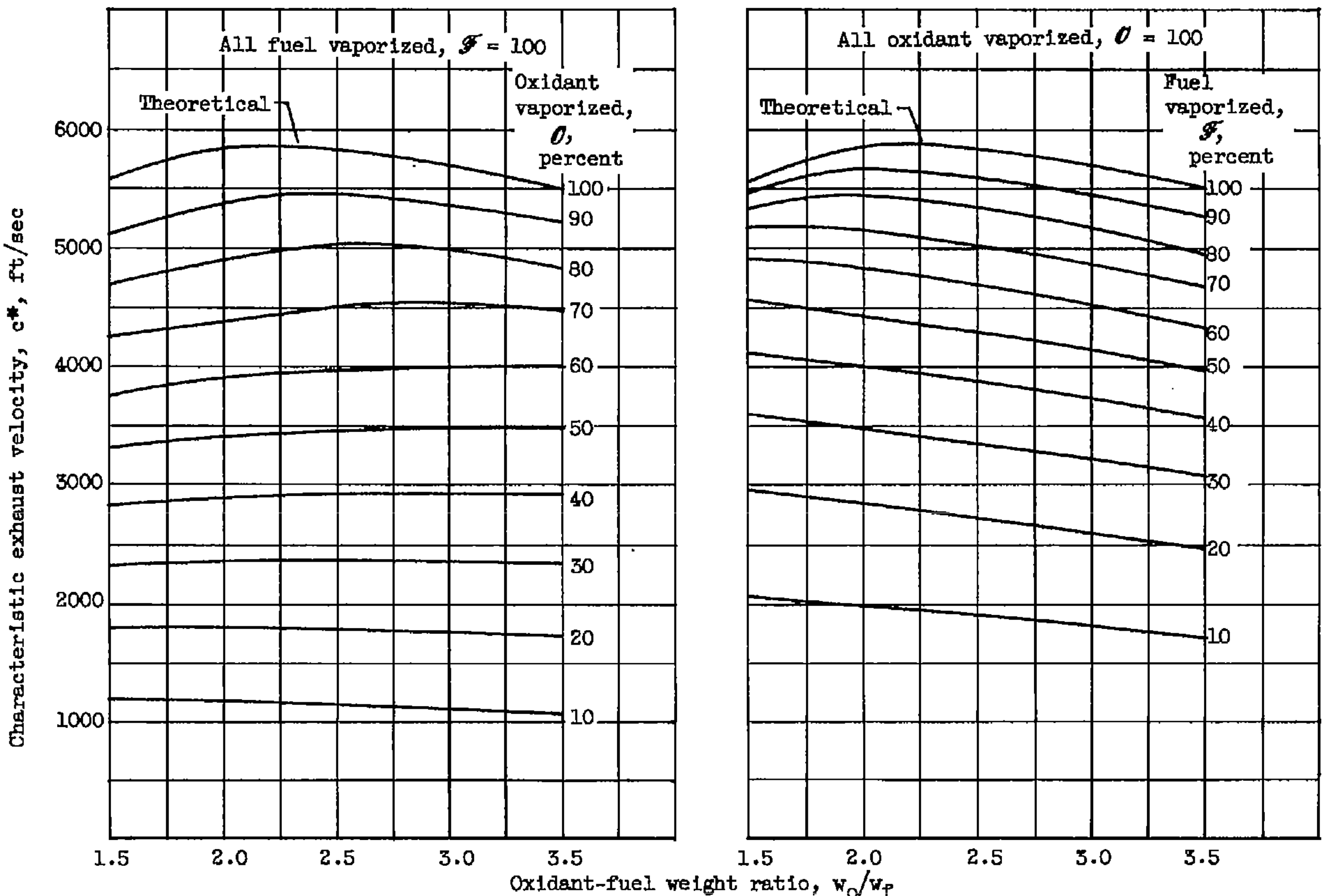
(a) Variation of c^* with mixture ratio.

Figure 4. - Effect of incomplete vaporization on c^* and c^* efficiency for ammonia and fluorine.



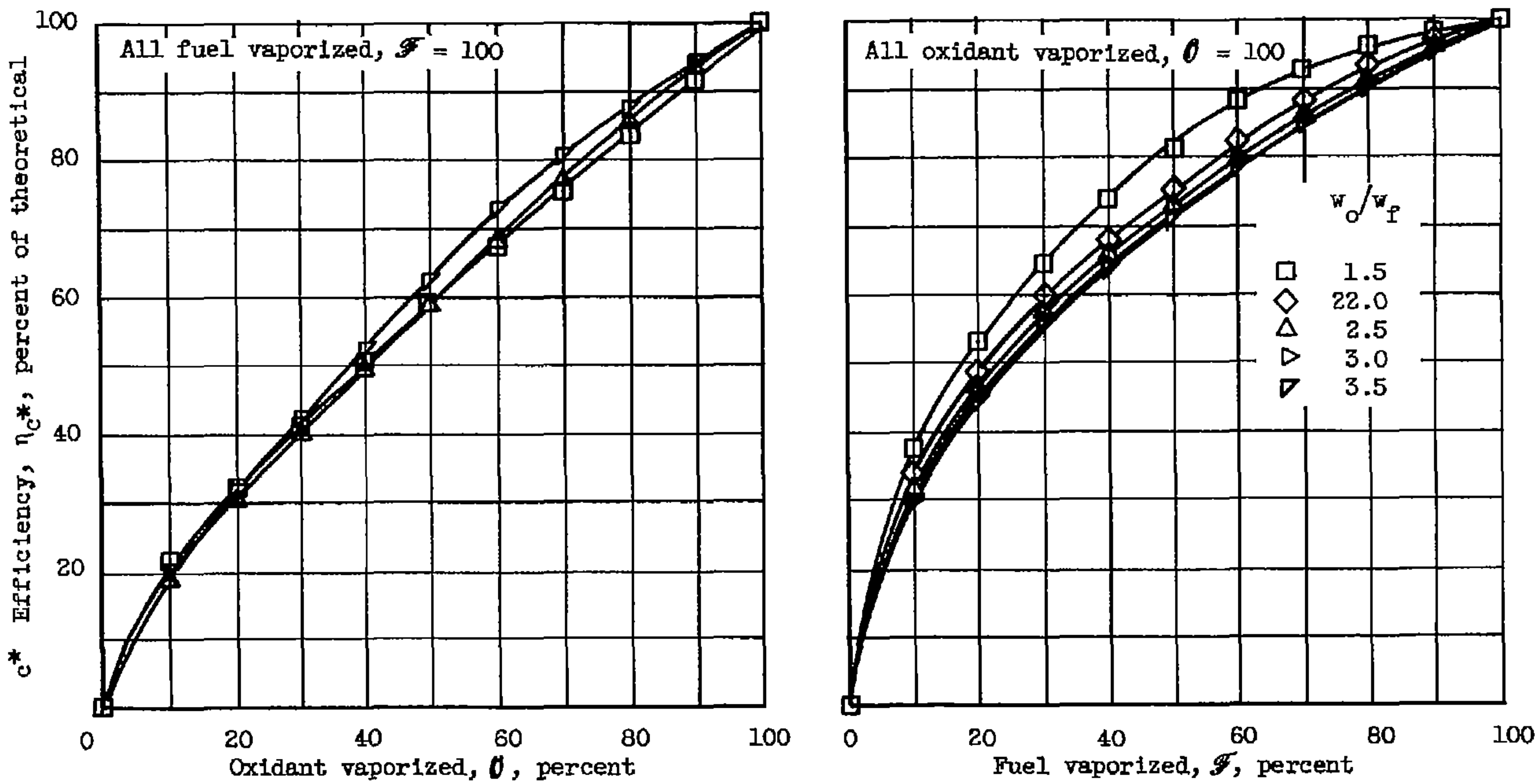
(b) Variation of c^* efficiency with percentage of propellant vaporized.

Figure 4. - Concluded. Effect of incomplete vaporization on c^* and c^* efficiency for ammonia and fluorine.



(a) Variation of c* with mixture ratio.

Figure 5. - Effect of incomplete vaporization on c* and c* efficiency for JP-4 and oxygen.



(b) Variation of c^* efficiency with percentage of propellant vaporized.

Figure 5. - Concluded. Effect of incomplete vaporization on c^* and c^* efficiency for JP-4 and oxygen.

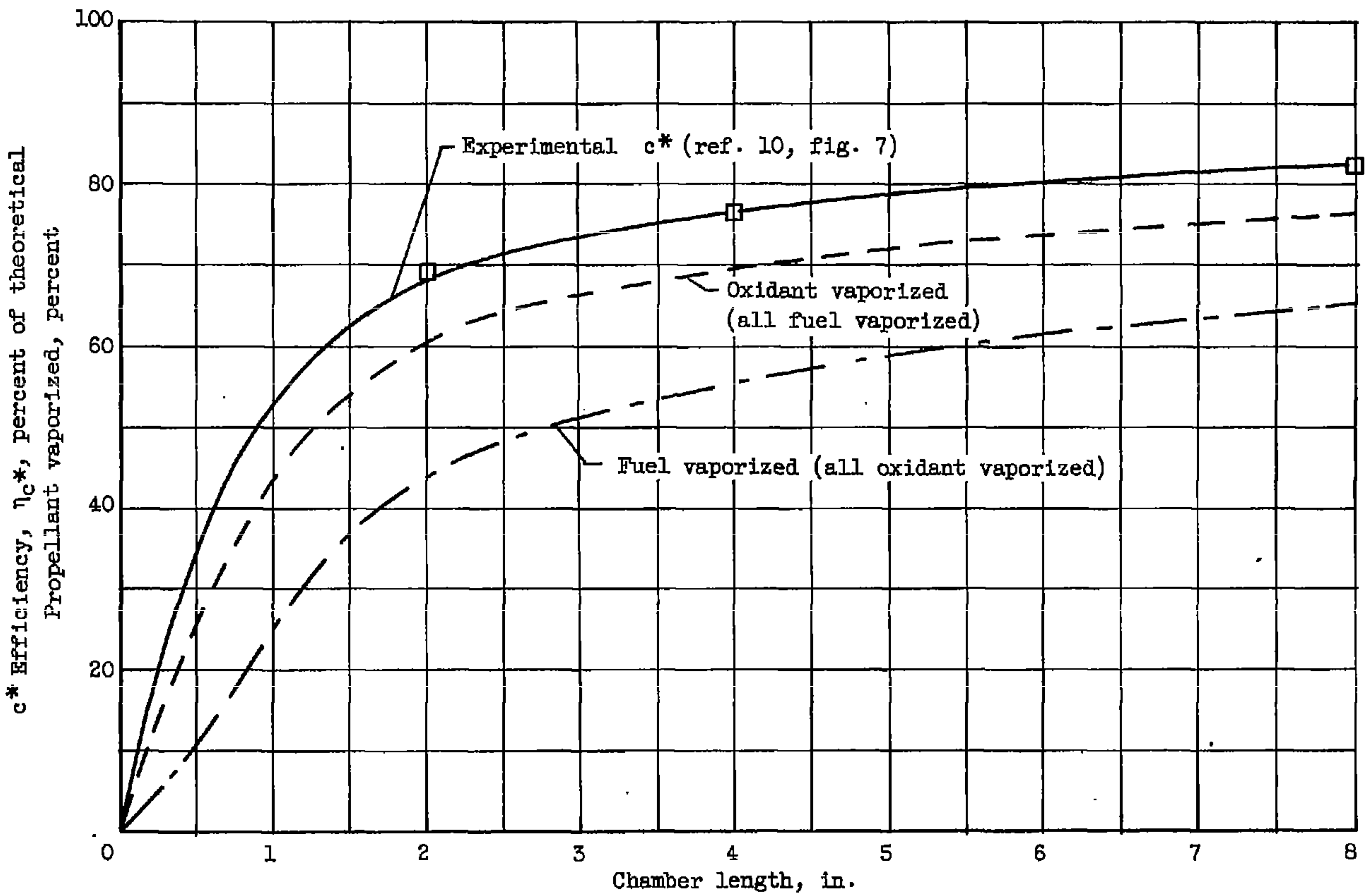


Figure 6. - Evaluation of typical performance data for percentages of fuel and oxidant vaporized. Propellants, oxygen and JP-4; oxidant-fuel weight ratio, 2.2.

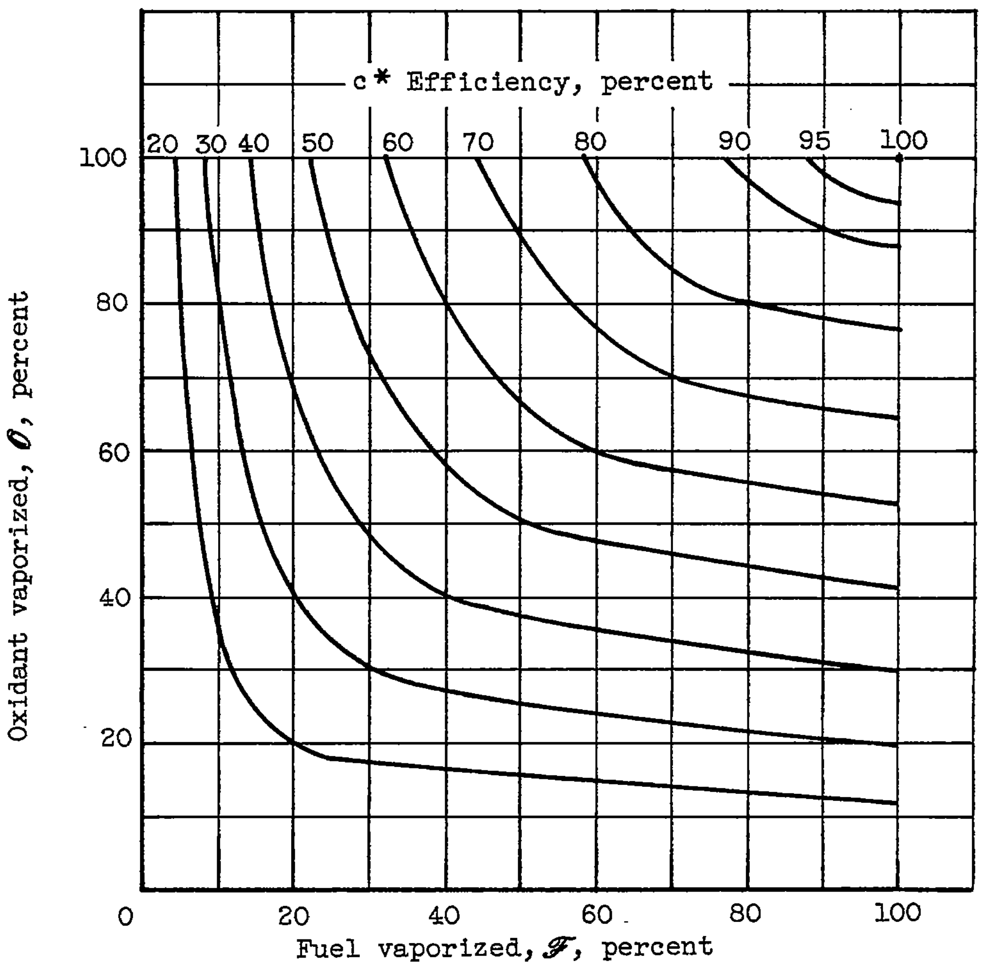


Figure 7. - Percentages of vaporized fuel and oxidant required to maintain a given c* efficiency. Propellants, JP-4 and oxygen; oxidant-fuel weight ratio, 2.2.

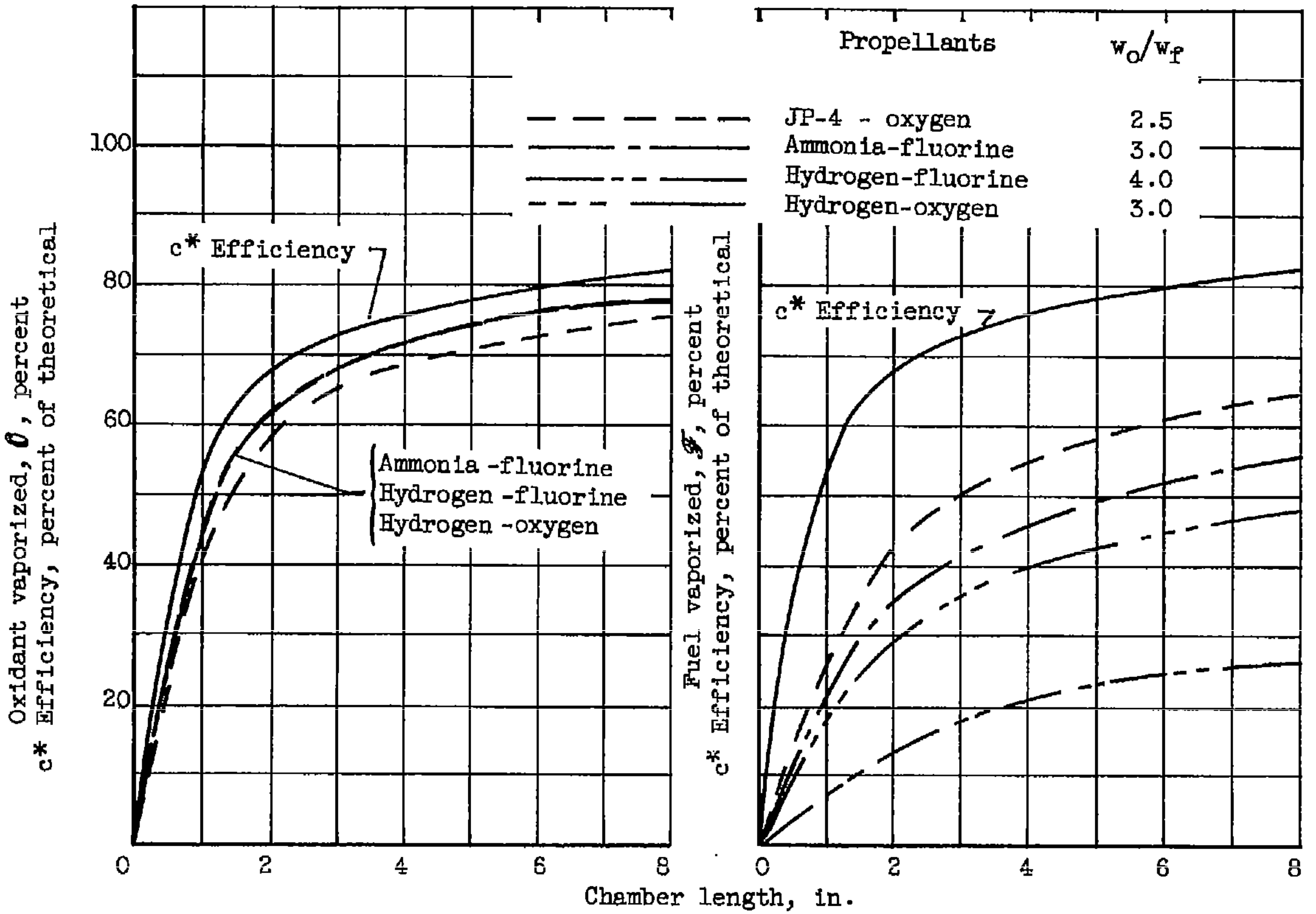


Figure 8. - Comparison of calculated percentages of propellant vaporized for several propellant combinations, using a typical experimental variation of c* with chamber length.

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